1. NASA Glenn Research Center Battery Activities Overview – for the NESC Battery Working Group Meeting in Houston, TX – June 20, 2009

NASA Glenn Research Center Battery Activities Overview

Michelle A. Manzo
NASA Glenn Research Center

This paper will provide an overview of the planned energy storage systems for the Orion Spacecraft and the Aries rockets that will be used in the return journey to the Moon and GRC's involvement in their development. Technology development goals and approaches to provide batteries and fuel cells for the Altair Lunar Lander, the new space suit under development for extravehicular activities (EVA) on the Lunar surface, and the Lunar Surface Systems operations will also be discussed.

ABSTRACT

NASA Glenn Research Center Battery Activities Overview

NESC Battery Working Group Meeting
Houston, TX
June 30, 2009

Michelle A. Manzo
NASA Glenn Research Center

- Introduction
- Constellation Projects
  - *Ares I* Crew Launch Vehicle (CLV)
  - *Orion* Crew Exploration Vehicle (CEV)
  - *Altair* Lunar Lander
  - *Ares V* Cargo Launch Vehicle
  - *Extra Vehicular Activity (EVA) Suits*
  - *Lunar Surface Systems*
- Technology Development
  - *Exploration Technology Development Program – Energy Storage Project*
    - *Li-ion Batteries*
    - *PEM Fuel Cells*
    - *PEM Regenerative Fuel Cells*
- NESC Battery Working Group
- ISS Batteries – Penni Dalton

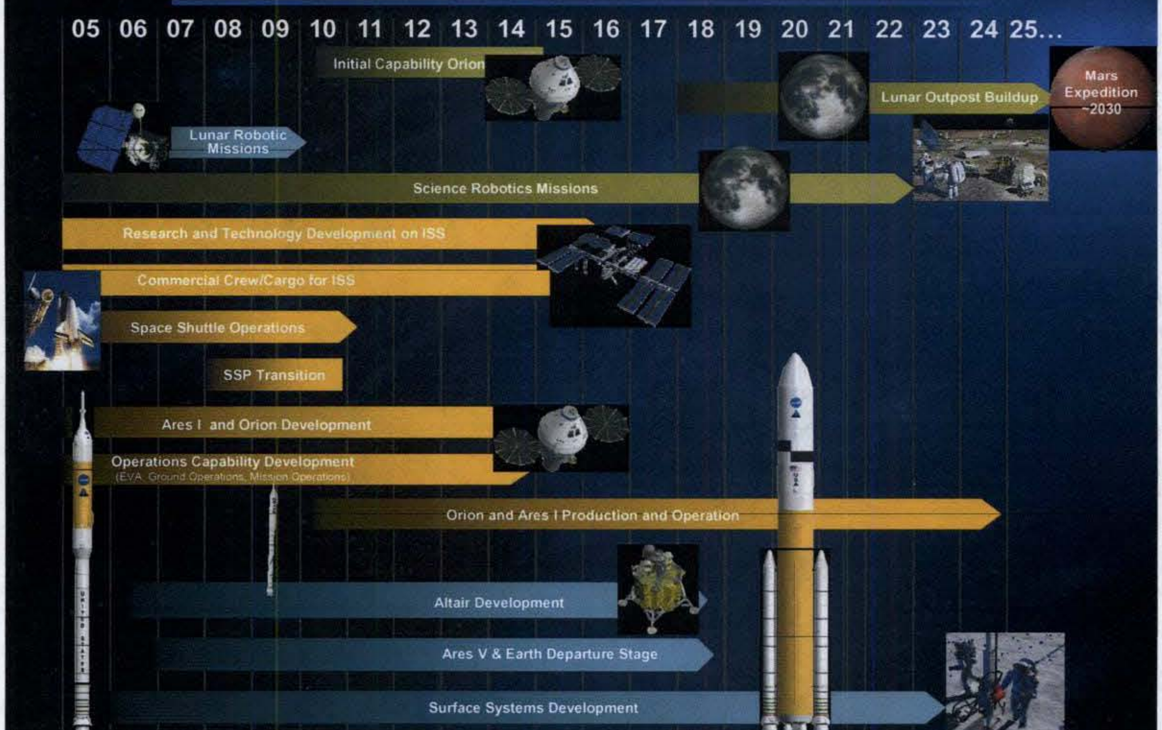
U.S. Space Exploration Policy

- Safely fly the Space Shuttle until 2010
- Complete the International Space Station (ISS)
- Develop a balanced program of science, exploration, and aeronautics
- Develop and fly the Orion Crew Exploration Vehicle (CEV)
- Land on the Moon no later than 2020
- Promote international and commercial participation in exploration

"The next steps in returning to the Moon and moving onward to Mars, the near-Earth asteroids, and beyond, are crucial in deciding the course of future space exploration. We must understand that these steps are incremental, cumulative, and incredibly powerful in their ultimate effect."

– NASA Administrator Michael Griffin
October 24, 2006

NASA's Exploration Roadmap




Constellation Leverages Unique Skills and Capabilities Throughout NASA Centers
Ames
• Lead Thermal Protection System ADP
• Aero-Aerothermal database
• Ares Abort simulations
• Software and GN&C support
Glenn
• Lead Service Module and Spacecraft Adapter integration
• Flight Test Article "Pathfinder" fabrication
• Ares I-1 upper stage simulator lead
• Ares power, TVC and sensors lead
• J-2X altitude/inspace testing
• SE&I Support
• EVA, Power, Communications, Avionics, and Informatics Lead
Goddard
• Communications Support
Dryden
• Lead Abort Flight Test Integration/Operations
• Abort Test Booster procurement
• Flight Test Article Development/ Integration
Langley
• Lead Launch Abort System integration
• Lead landing system ADP
• Ares I-1 vehicle integration
• Ares aerodynamics lead
• SE&I Support
JPL
• Thermal Protection System support
Kennedy
• Home for Ground Ops Project
• Ground processing
• Launch operations
• Recovery operations
Johnson
• Home for Program
• Home for Projects: Orion, Mission Ops, EVA, Lunar Lander
• Lead Crew Module integration
• Orion Spacecraft Integration
• GFE projects management
• Flight Test Program
Stennis
• Rocket Propulsion Testing for Ares
Marshall
• Home for Ares Project
• Ares I and V development and integration lead
• LAS and SM SE&I Support

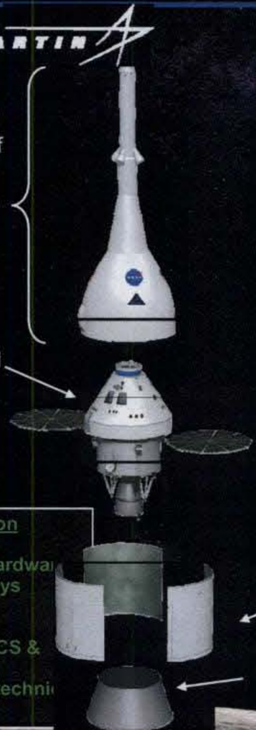

NASA Exploration Mission Energy Storage Options
Near-term
• Orion (Crew Exploration Vehicle, CEV)
• Ares I (Crew Launch Vehicle, CLV)
• Ares V (Cargo Launch Vehicle, CaLV)
Lithium-ion baselined for Ares I and Orion
Far-term
• Lunar Precursor and Robotics Program (LPRP)
• Lunar Surface Access Module (Altair)
• Rovers, Habitats and EVA
Battery, fuel cell, regenerative fuel cell energy storage technologies under development

Orion - Crew Exploration Vehicle

LOCKHEED MARTIN

Launch Abort System (LAS)
- Emergency escape of Crew Module during launch

Crew Module (CM)
- Pressurized crew and cargo transport
- Only component that returns to Earth for potential re-use.



Service Module (SM)
- Propulsion, electrical power, and fluids storage

Encapsulated Service Module (ESM) Panels

Spacecraft Adapter
- Structural transition to launch vehicle

Lockheed Martin /Hamilton Sundstrand team:
- Honeywell - Avionics hardwa
- ATK-Goleta - Solar Arrays
- Orbital - Launch Abort System (LAS)
- Aerojet - propulsion (RCS & LAS motor)
- NASA - oversight and techni support

- System Voltage 120 Volts
- Both SM and CM operate as separate vehicles at end of mission

Batteries – Yardney
- Crew Module
  - 32 cells, 30AH NCP25-1 (Mars Lander Cells)
  - 4 batteries
- Service Module
  - 32 cells, 7 AH
  - 2 batteries

Orion Lithium-Ion Battery

Operational Requirements
- >6000 LEO Cycles at 20%DOD, 14 cycles at 100% DOD
- Mission length – 235 days
- 50-68°F – Operating range, excursions 30 day cumulative to 104°F

CM Battery
- Target mass 88lbs
- Volume allocation 13.6 in. width, 17.6 in length, and 13.4 in height

Current design exceeds mass and volume

SM Battery – design still in preliminary stages
- Estimated mass 35 lbs
- Volume allocation - 12.4 in width, 16.8 in length, and 11 in height

Designs are fluid – common batteries are under consideration

Ares I - Crew Launch Vehicle

Encapsulated Service Module (ESM) Panels

Orion CEV

Instrument Unit

- Primary Ares I control avionics system
- *NASA Design* / *Boeing Production*

Stack Integration

- 927k kg (2.0M lbm) gross liftoff weight
- 99 m (325 ft) in length
- *NASA-led*

First Stage

- Derived from current Shuttle RSRM/B
- Five segments/Polybutadiene Acrylonitrile (PBAN) propellant
- Recoverable
- New forward adapter
- Avionics upgrades
- *ATK Launch Systems ($1.8B)*

Interstage

Upper Stage

- 137k kg (305k lbm) LOX/LH_2 stage
- 5.5 m (18 ft) diameter
- Aluminum-Lithium (Al-Li) structures
- Instrument unit and interstage
- Reaction Control System (RCS) / roll control for first stage flight
- Primary Ares I control avionics system
- *NASA Design* / *Boeing Production*

Upper Stage Engine

- Saturn J–2 derived engine (J–2X)
- Expendable
- *Pratt and Whitney Rocketdyne ($1.2B)*

Ares I ~ Upper Stage Batteries

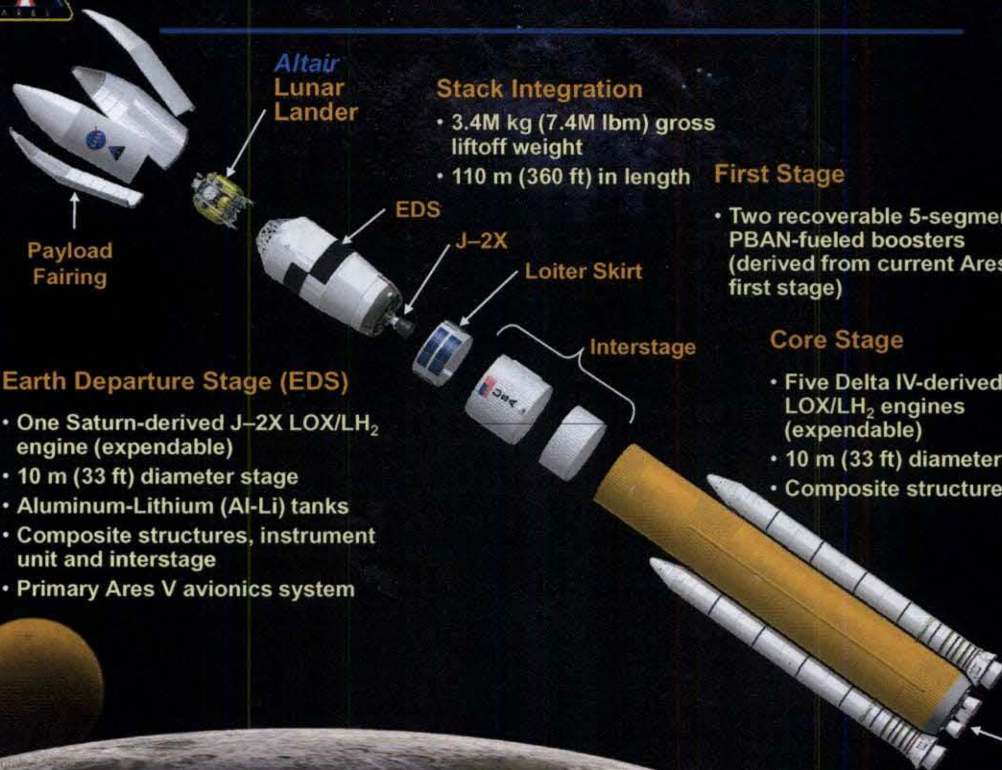
- Upper Stage – (Single Failure Tolerant)
  - Instrument Unit (IU):
    - Two Power Busses (1 kW average per Bus)
      - Two 16 A-Hr Li-Ion Batteries for EPS
  - Aft Skirt:
    - Two Power Busses (3.4 kW average per Bus)
      - Two 16 A-Hr Li-Ion Batteries
  - Flight (Range) Safety System: Silver Zinc Batteries (heritage)
- Interstage
  - Three Power Busses (500 W average per Bus)
- First Stage:
  - 55 A-Hr Silver-Zinc Batteries (heritage)

BOEING

Instrument Unit Avionics Contractor

Common US Battery Line Replaceable Unit Concept
16 Amp-Hr, 22 lbs

Ares V Elements



Stack Integration
- 3.4M kg (7.4M lbm) gross liftoff weight
- 110 m (360 ft) in length

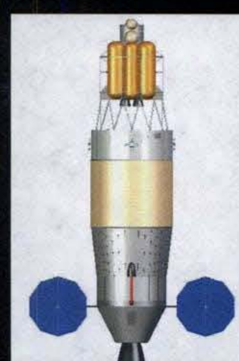
First Stage
- Two recoverable 5-segment PBAN-fueled boosters (derived from current Ares I first stage)

Core Stage
- Five Delta IV-derived RS–68 LOX/LH_2 engines (expendable)
- 10 m (33 ft) diameter stage
- Composite structures

Earth Departure Stage (EDS)
- One Saturn-derived J–2X LOX/LH_2 engine (expendable)
- 10 m (33 ft) diameter stage
- Aluminum-Lithium (Al-Li) tanks
- Composite structures, instrument unit and interstage
- Primary Ares V avionics system

Ares V Electrical Power

- **Earth Departure Stage (EDS)**
  - Design Drivers:
    - Electrical Power for Earth orbit loiter
    - Electrical power transfer to *Altair* Lunar Lander
      - Launch through trans-lunar injection (TLI) burn
  - Design Alternatives:
    - **Solar Array & Lithium-Ion Battery**
      - Provides for indefinite loiter times
      - Lower heat rejection requirements
      - Opportunity for commonality with Orion systems
    - **Primary Fuel Cell**
      - Opportunity for commonality with Lander systems
      - Performance not impacted by vehicle attitude during loiter
      - No significant mechanisms required
      - TLI loads should not be an issue



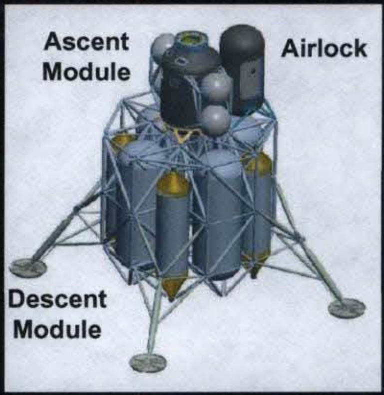
- **Core Stage Systems**
  - Batteries & Power Distribution Units
  - Flight (Range) Safety System Batteries

- **Solid Rocket Booster (SRB)**
  - Thrust Vector Control: electro-hydrostatic actuators (EHAs) under consideration
  - May require high-voltage battery

Altair Energy Storage Requirements

Descent Module: Baseline – Primary PEM Fuel Cell

- 3 kW nominal , 6 kW peak, 220 hours continuous operation.
  - Sortie: Power Lander for 9 days continuous (7 days surface)
  - Outpost: 3 days continuous power (1 day on surface)
- Should operate until all residual propellants converted to water/power
- Must operate with expected fuel and oxidant contamination levels of residual lander propellants.
- Must remove dissolved gases from water by-product during all phases of the mission, including in 0-g.
- Human-safe operation from 0 – 30°C and 0 – 1 G.



Ascent Module: Baseline Primary LiMnO2 Battery

- Baseline battery 121.6 kg, 22.7 kW-hour sized for an ascent underburn.
- Human-safe operation from 0 – 30°C and 0 – 1 G.

LDAC-3 design
Assumes no single-point failures, and 2-string redundancy on battery to minimize LOC.
Baselines primary battery

Altair Energy Storage System Options

- **Replacing primary battery for ascent stage with very high energy, low cycle secondary will address key risks associated with primary batteries:**
  - Inability to verify proper battery function in-flight before critical use;
  - Probable large mass impact when peak/average power ratios defined;
  - Increased mass and volume to address potential Altair need for power in excess of the 1500 W power transfer requirement from Orion & EDS identified in LDAC3
- **Rechargeable batteries can eliminate these risks; but mass should not increase appreciably**
  - 160 – 200 W-hr/kg at the battery level may be sufficient.
  - Nominally ten recharge cycles are required with 1.67 kW nominal power and 2 kW peak power, operating for 7 hours continuously.
  - Human-safe operation from 0 – 30°C and 0 – 1 G.

Lunar Extravehicular Activity Suit

Greatly increased electronic capability (HDTV, communications node, drives need for high energy batteries in small, low-mass package. Very high specific energy and energy density with 8-hour, human-safe operation drives technology development.

Preliminary Battery Requirements:

Human-safe operation

~ 1155 W-Hr energy

8 hours continuous operation

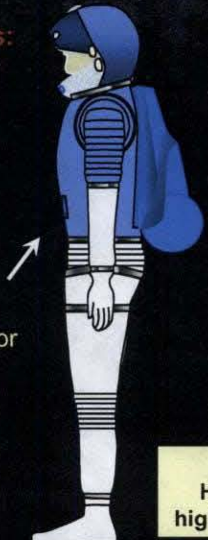
~ 144 W average power

233 W max power

Current mass allocation: 5 kg

Current volume allocation: 3 liters

100 cycles (operation every other day for six months)



Prioritized mission requirements: Human-safe operation; 8-hr duration; high specific energy; high energy-density.

Lunar Surface Systems

Scenario-Based Planning:

Rechargeable batteries and/or regenerative fuel cells for power & support unit, portable utility pallet, and/or mobility systems

- Power & Support Unit
  - Mass: PSU 2,867 kg / SSU 680 kg
  - Energy storage: 720 kWh Regenerative Fuel Cells
  - Power generation: 11.2 kW net, 9 meter solar array
  - Power consumables storage: 337 kg oxygen, 43 kg hydrogen; 450 kg water x 2 (power and scavenge)
- Crew Mobility Chassis Specifications
  - 969 kg dry vehicle mass, >100 km range, upgradable with PUPs
  - 0-5 kph low gear, 0-20 kph high gear
  - 20 kWh onboard energy storage (Li-ion battery)
  - 5.9 kW peak power, 1.15 kW average power and 125 W standby power.
  - Nominal drive time is 87 hours and stand-by time is 800 hours.
- Portable Utility Pallet
  - Logistics: 25 kg Oxygen, 90 kg Water, 90 kg Wastewater
  - Power Generation: 4.4-kW, 5.5-meter Orion-class array
  - Energy Storage: 10 kWh (Li-ion batteries)
  - Mass: 708.9 kg (dry), 963.4 kg (wet)

Lunar Surface Systems

Potential Requirements

- Modular power system
- ~20-40 kW lunar daytime power level
- ~10-20 kW lunar nighttime power level
- 5,000 hr operational life at poles
- >10,000 hr operational life beyond poles
- 5-10 year calendar life
- 100 -1000+ discharge/recharge cycles
- Thermal, dust, launch/landing, vacuum environments
- Reliable, human-rated operation in thermal, dust, launch/landing, vacuum environments
- Autonomous control and operation
- Human-rated
- Low mass and volume
- Little or no maintenance needs

Fuel Cell /Regenerative Fuel Cell Needs

- 5,000 hr operational life at poles
- >10,000 hr operational life beyond poles
- 100 -1000+ discharge/recharge cycles
- Compatible with H_2/O_2 tanks at 2000 psi

Battery Needs

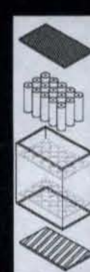
- 10-hour discharge and 10-hour charge
- 2000 discharge/recharge cycles
- Temperature controlled to 0 – 30°C
- 5 year calendar life

Exploration Technology Development Program
Energy Storage Project

Project Objective: Reduce risks associated with the use of batteries, fuel cells, and regenerative fuel cells for *Altair, Lunar Surface Systems, and EVA*.

Project TRL-6 Deliverables:

- **Primary fuel cell** for *Altair* Descent Stage
- **Regenerative fuel cell** for Lunar Surface Power Units and Mobility Systems
- **Rechargeable battery cells** for *Altair* Ascent Stage, EVA Suit 2, Lunar Surface Mobility Systems



Lithium-based Battery Technology:
Develop Lithium-based cells for human-rated, reliable operation with very high specific energy.

Fuel cell technology:
Develop proton-exchange-membrane stack and balance-of-plant technology to increase system lifetimes and reduce mass, volume and parasitic power.

Regenerative fuel cell technology:
Develop balanced high-pressure electrolyzers and thermal management and reactant processing technologies for integrated electrolyzer/fuel cell.

Energy Storage Project WBS

1.0 Project Management

1.1 Project Management
1.2 Systems Assessments

7.0 Education and Public Outreach

GRC Led Project

Carolyn Mercer
Project Manager

Amy Jankovsky
Integration Manager

2.0 Lithium-Ion Batteries

2.1 Battery Task Management

2.2 High Energy Cell (for LSS)
- 2.2.1 HE-Unique Component Develop.
- 2.2.2 HE Cell Development
- 2.2.3 HE KPP Assessments

2.3 Ultra-High Energy Cell (for EVA & Altair)
- 2.3.1 UHE Component Development
- 2.3.2 UHE Cell Development
- 2.3.3 UHE KPP Assessments

2.4 Safety, Packaging, and Control
- 2.4.1 Cell Configuration
- 2.4.2 External Safety Devices
- 2.4.3 Control Methodologies

GRC, JPL, JSC Participants

Concha Reid, Tom Miller
Co-PI

3.0 Fuel Cell Systems

3.1 Fuel Cell Task Management

3.2 Primary Fuel Cell Development
- 3.2.1 Stacks
  - 3.2.1.1 Baseline Stacks
  - 3.2.1.2 Alternative Stacks
- 3.2.2 BOP and System Testing

3.3 High-P Electrolysis Development

3.4 Regenerative Fuel Cell Technology

3.5 Cross-Cutting Tech Development
- 3.5.1 Passive Thermal Control
- 3.5.2 Advanced MEAs

GRC, JPL, JSC, KSC Participants

Mark Hoberecht
PI

Grayed elements unused in FY09

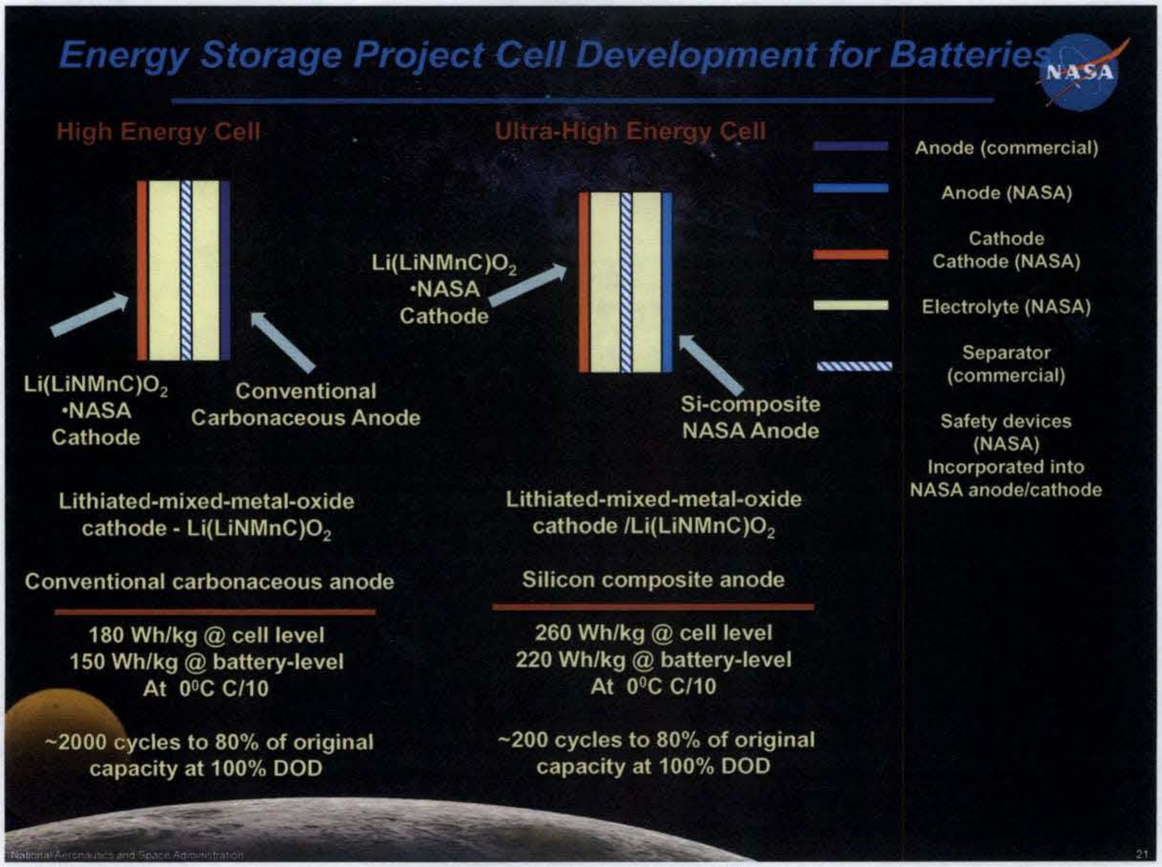
Li-Ion Battery Development

Objectives: Develop Flight Qualified, Human-Rated Li-Ion cells with increased reliability and mass and volume reductions

Approach:

- **Identify chemistries most likely to meet overall NASA goals and requirements within allotted development timeframe**
  - "High energy" and "ultra high energy" cells targeted to meet customer requirements.
- **Utilize in-house and NRA Contracts to support component development**
  - Develop components to increase specific energy (anode, cathode, electrolyte)
  - Develop low-flammability electrolytes, additives that reduce flammability, battery separators and functional components to improve human-safety;
  - Charge methodology
- **Engage industry partner - multi year contract**
  - Provide recommendations for component development / help screen components
  - Scale-up components (core)
  - Manufacture evaluation and screening cells
  - Design and optionally manufacture flightweight cells that address NASA's goals
- **Complete TRL 5 and 6 testing at NASA**
- **Leverage outside efforts**
  - Utilize SBIR/IPP efforts
  - Leverage work at DoE and other government agencies

Cell development TRL definitions
TRL 4: Advanced cell components integrated into a flight design cell
TRL 5: Performance testing on integrated cell shows goals met
TRL 6: Environmental testing on cell (vibration, thermal) shows robust performance



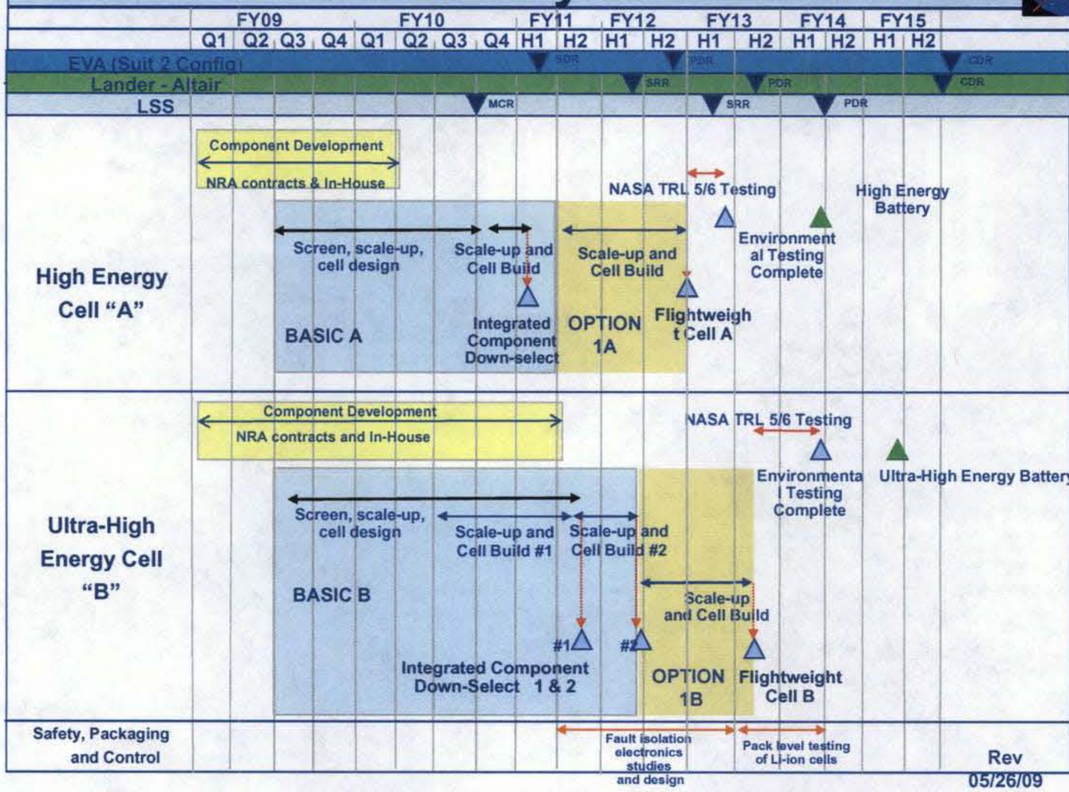
Key Performance Parameters for Battery Technology Development

Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a moderate reduction in the performance with flame retardants and non-flammable electrolytes	Benign cell venting without fire or flame and reduce the likelihood and severity of a fire in the event of a thermal runaway	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and external short circuit with no fire or flame
Specific energy Lander: 150 – 210 Wh/kg 10 cycles Rover: 160 – 200 Wh/kg EVA: 270Wh/kg 100 cycles	**Battery-level** specific energy*	90 Wh/kg at C/10 & 30°C 83 Wh/kg at C/10 & 0°C (MER rovers)	130 Wh/kg at C/10 & 30°C 120 Wh/kg at C/10 & 0°C	**135** Wh/kg at C/10 & 0°C "High-Energy"** **150** Wh/kg at C/10 & 0°C "Ultra-High Energy"**	**150** Wh/kg at C/10 & 0°C "High-Energy" **220 Wh/kg at C/10 & 0°C "Ultra-High Energy"**
	Cell-level specific energy	130 Wh/kg at C/10 & 30°C 118 Wh/kg at C/10 & 0°C	150 Wh/kg at C/10 & 0°C	**165** Wh/kg at C/10 & 0°C "High-Energy" **180** Wh/kg at C/10 & 0°C "Ultra-High Energy"	**180** Wh/kg at C/10 & 0°C "High-Energy" **260** Wh/kg at C/10 & 0°C "Ultra-High Energy"
	Cathode-level specific capacity $Li(LiNiMn)O_2$	180 mAh/g	$Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_2$: 240 mAh/g at C/10 & 25°C $Li(Li_{0.2}Ni_{0.13}Mn_{0.54}Co_{0.13})O_2$: 250 mAh/g at C/10 & 25°C 200 mAh/g at C/10 & 0°C	**260** mAh/g at C/10 & 0°C	**280** mAh/g at C/10 & 0°C
	Anode-level specific capacity	280 mAh/g (MCMB)	350 mAh/g (MPG-111) 450 mAh/g Si composite	**600** mAh/g at C/10 & 0°C (with Si composite)	**1000** mAh/g at C/10 0°C (with Si composite)
Energy density Lander: 311 Wh/l Rover: TBD EVA: 400 Wh/l	**Battery-level** energy density	250 Wh/l	n/a	**270** Wh/l "High-Energy" **360** Wh/l "Ultra-High"	**320** Wh/l "High-Energy" **420** Wh/l "Ultra-High"
	Cell-level energy density	320 Wh/l	n/a	**385** Wh/l "High-Energy" **460** Wh/l "Ultra-High"	**390** Wh/l "High-Energy" **530** Wh/l "Ultra-High"
Operating environment 0°C to 30°C, Vacuum	Operating temperature	-20°C to +40°C	-50°C to +40°C	**0°C** to **30°C**	**0°C** to **30°C**

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.
*** Battery values are assumed at 100% DOD, discharged at C/10 to 3.000 volts/cell, and at 0°C operating conditions**
**** "High-Energy" = Exploration Technology Development Program cathode with MCMB graphite anode**
"Ultra-High Energy" = Exploration Technology Development Program cathode with Silicon composite anode

Revised 5/19/09

Lithium-Based Battery Master Schedule



Ultra High Energy Battery Feasibility Study

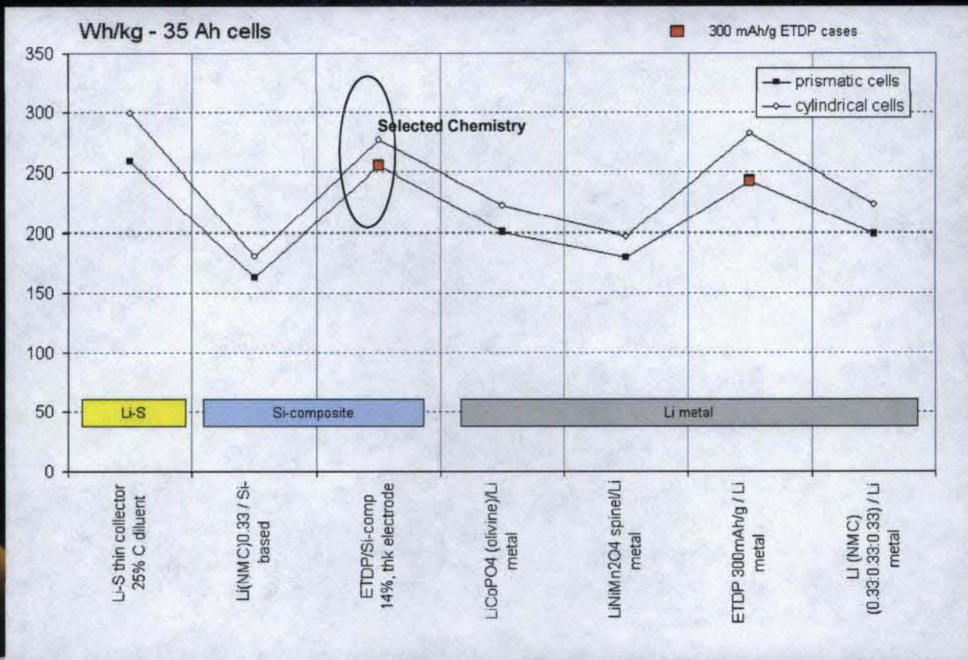
Attribute Weights

Attribute	Final Weight
Safety	17.9
Rate Capability up to C/5	15.6
Specific Energy	15.0
Storage and Calendar Life	12.2
Energy Density	10.2
Manufacturability	8.3
Schedule	8.0
Cost to TRL 6	6.5
Cycle Life	3.8
Rate Capability up to C/2	2.5

Chemistry Options

Cathode	Anode
$Li(LiNMC)O_2$ (ETDP)	Si-Based Composite
$Li(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$	Si-Based Composite
$Li(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$	Li Metal
$Li(LiNMC)O_2$ (ETDP)	Li metal
$LiNiMn_2O_4$	Li metal
$LiCoPO_4$	Li metal
$(Li_2)S$	Li metal

Cell Level Specific Energy Projections of Final Chemistry Options



Advanced Chemistry Options and Final Weights

Cathode	Anode	Final Weight
$Li(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$	Si-based Composite	20.2
$Li(LiNMC)O_2$ (ETDP)	Si-based Composite	17.0
$LiNiMn_2O_4$	Li metal	15.3
$Li(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$	Li metal	13.9
$Li(LiNMC)O_2$ (ETDP)	Li metal	13.1
$(Li_2)S$	Li metal	11.5
$LiCoPO_4$	Li metal	9.1

- Li(NMC) cathode with Si-based composite anode offers:
  - Higher safety, manufacturability and rate capability
  - Lower specific energy
- ETDP cathode with Si-based composite anode offers:
  - Higher specific energy
  - Lower safety, manufacturability and demonstrated rate capability

NASA Research Announcement NNC08ZP022N Research and Development of Battery Cell Components

- **Contracts Awarded**
  - Georgia Tech Research Corp. & Clemson University, "Design of Resilient Silicon Anodes"
  - Lockheed Martin Space Systems Company, "Advanced Nanostructured Silicon Composite Anode Program"
  - University of Texas at Austin, "Development of High Capacity Layered Oxide Cathodes"
  - NEI Corp., "Mixed Metal Composite Oxides for High Energy Li-ion Batteries"
  - Yardney, "Flame-retardant, Electrochemically Stable Electrolyte for Lithium-ion Batteries"
  - Giner, "Control of Internal and External Short Circuits in Lithium-Ion Batteries"
  - Physical Sciences, "Metal Phosphate Coating for Improved Cathode Material Safety"

Battery SBIRs and STTRs

- **Phase I SBIRS**
  - Yardney Technical Products –Advanced Battery Materials for Rechargeable Advanced Space-Rated Li-Ion Batteries
  - Superior Graphite Co. –SiLix-C Nanocompositesfor High Energy Density Li-ion Battery Anodes
  - Physical Sciences, Inc. –Silicon Whisker and Carbon Nanofiber Composite Anode
  - TH Chem, Inc. –New Li Battery Chemistry for Improved Performance
  - TDA Research, Inc. --High Capacity Anodes for Advanced Lithium Ion Batteries
  - EIC Laboratories, Inc. –Nanoshell Encapsulated Li-ion Battery Anodes for Long Cycle Life
  - Giner, Inc. –Non-Flammable, High Voltage Electrolytes for Lithium Ion Batteries
- **Phase II SBIR - Yardney Technical Products –Nano-Engineered Anode Materials for Rapid Recharge High Energy Density Lithium-ion Batteries**
- **STTR - NEI Corporation - High capacity and high voltage composite oxide cathode for Li-ion batteries**

Anodes

- Goal: 1000 mAh/g at C/10 and 0°C: > 3X the capacity of SOA Li-ion anodes
- Significant results to date:
  - Pursuing multiple approaches to develop Silicon-based composite anodes that will enable the specific energy and cycle life goals. Combination of in-house and NRA development activities.
    - First NRA deliverables from Georgia Tech have been evaluated (ETDP-3 GT)
      - 406 mAh/g after 5 cycles at C/20 and 23°C
      - Translates to ~ 368 mAh/g respectively at C/20 and 0°C
    - Preliminary results from Lockheed Martin NRA:
      - 1592 mAh/g after 3 cycles at ~C/30 and 23°C,
      - 1^{st} cycle irreversible capacity loss = 306 mAh/g
      - Translates to ~1433 mAh/g at C/30 and 0°C
    - In-house anode synthesis capability established at GRC
      - Complementary approaches being pursued with deliverables Oct 2009
        - Modified resorcinol/formaldahyde gel
        - Thin Si film in 3D carbon structure

Technology Challenges	Current Approaches to Address
Minimize volume expansion during cycling	•Pursuing various approaches to optimize the anode structure to accommodate volume expansion of the silicon •Nanostructured Si composite absorbs strain, resists active particle isolation on cycling •Incorporation of elastic binders in Si –graphite and Si-C matrices •Improvement of mechanical integrity by fabricating structure to allow for elastic deformation
Minimize irreversible capacity loss	•Protection of active sites with functional binder additives •Pre-lithiation approaches are possible •Nanostructured Si resists fracture and surface renewal
250 cycles	Loss of contact with active particles reduces cycle life. Addressing volume changes and improvement of mechanical integrity will improve cycle life

Cathodes

- **Goals:**
  - Specific capacity of 280 mAh/g at C/10 and 0°C to 3.0 V
  - High voltage operation to 4.8 V
  - Improved thermal stability over conventional Li-ion cathodes
- **Significant Results to date:**
  - Baselined cathode material compositions/structures that are inherently more thermally stable than conventional Li-ion cathode materials
  - Achieved 280 mAh/g at C/20 and room temp between 4.8 and 2.0V in small lab scale testing ($Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O_2$ with Al_3O_2 coating from UT Austin)
    - Translates to ~239 mAh/g at C/20 and 0°C to 3.0 V
  - Achieved 210-220 mAh/g at C/10 and room temp between 4.8 and 2.0V ($Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O_2$ uncoated=NEI-D)
    - Translates to ~180-188 mAh/g at C/10 and 0°C to 3.0 V
    - Successfully synthesized in large batch sizes
  - Operation to 4.8V demonstrated with good reversibility
    - Cathodes tested with several electrolyte formulations (need compatible electrolytes to

Technology Challenges	Current Project Approaches to Address
High specific capacity at practical discharge rates	•Vary stoichiometry to determine optimum chemical formulation •Reduce particle size •Experiment with different synthesis methods to produce materials with physical properties such that their specific capacity is retained on production scale
Low volume per unit mass	•Vary cathode synthesis method to optimize properties that can: •Improve energy density •Improve ability to cast cathode powders •Facilitate incorporation of oxide coatings, which have the potential to increase rate capability and reduce capacity fade to extend cycle life
Minimize 1^{st} cycle irreversible capacity loss and	•Surface modification via coatings to improve cathode-electrolyte interfacial properties •Improves capacity retention

Separators

- **Goals:**
  - Identification of Li-ion cell separator materials that are compatible with the ETDP chemistry and provide an increased level of safety over SOA Li-ion cell separators
  - Current efforts are focused on assessment of developmental (i.e., company IRAD materials) and commercial separator materials
- **Significant results to date:**
  - Baseline separator identified (Tonen E20) and evaluated
    - Physical, thermal, electrical and mechanical properties measured and documented
  - Several promising commercial and IRAD materials identified and evaluated. Procured ,obtained, or negotiating for additional samples to evaluate for our purposes
    - Physical Sciences, Inc.
    - Exxon Mobil
    - Kynar PVDF resins
    - Porous Power Technologies Symmetrix separators
    - • Tonen polyethylene (PE)
    - • Celgard polypropelene (PP)
    - • Celgard PP/PE/PP trilayer
    - • Saft America ceramics
  - Example results for Symmetrix PVDF Separators developed by Porous Power Technologies:
    - As compared to baseline, higher porosity, lower ionic resistance, lower internal heat generation, and allows for higher power and rate capability
    - Fiber-reinforced separator material may suppress internal shorts at elevated temperatures by maintaining mechanical integrity
- **Technology Challenges:**
  - No significant technology challenges
  - Design optimization for high porosity and low ionic resistance to facilitate ionic conductivity while maintaining mechanical strength
  - Must "shutdown" cell reactions below 130 degrees C without shrinking or losing mechanical integrity

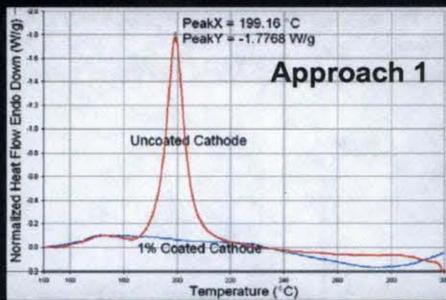
Electrolytes

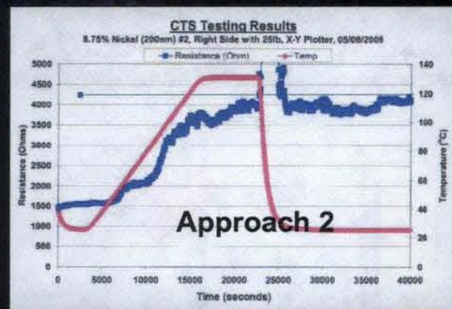
- **Goal: Develop flame-retardant and/or non-flammable electrolytes that are stable up to 5V**
- **Significant results to date:**
  - Demonstrated capability of flame-retardant electrolytes in experimental and prototype cells and determined the impact on life and rate capability (i.e., Gen 1 electrolyte observed to have comparable life to baseline system).
  - Investigated various electrolyte additives to improve high voltage cycling performance
    - No significant impact in high voltage performance cycling stability observed vs. baseline electrolyte
    - Determined baseline electrolyte is compatible with high voltage operation in cells with JPL-developed high voltage cathode, when evaluated in experimental cells using Li metal as anodes.
  - Examined the ability of linear carbonate type electrolytes to improve high voltage stability
    - No impact on high voltage performance observed
  - Assess the performance of flame-retardant additives in a high voltage system
    - Displayed rate performance between C/10 and C/2
    - Electrolytes with flame-retardant additives displayed some reduced power and life versus systems with the baseline electrolyte (i.e., the FRA-containing electrolyte delivered ~ 95% of the baseline electrolyte using a C/2 discharge rate).
  - Many investigations in small laboratory coin cells, may different results in a fully mature cell.

Technology Challenges	Current approaches to address
Electrolyte that is stable up to 5V	Experiment with different electrolyte formulations and additives with potential to improve high voltage stability. Study interactions at both electrodes
Non-flammable or flame retardant electrolyte	Develop electrolytes containing additives with known flame retardant properties. Perform flame retardance assessments on developments that exhibit suitable electrochemical performance
High voltage stable, non-flammable or flame retardant electrolyte (combination of both properties in one electrolyte system)	Combine flame retardant additives with electrolyte formulations with high voltage stability. Operate systems to high voltages and investigate impacts on power capability and life.
Electrolytes possessing the requisite physical properties to ensure good rate capacity (adequate conductivity) and compatibility (wettability).	Develop electrolytes that are not excessively viscous to ensure that the ionic conductivity is sufficiently high over the desired temperature range and the separator wettability is adequate.

Safety

- Goal: Cells that are tolerant to electrical and thermal abuse
- Significant results to date: Cathode particles with a coating display no exotherms up to 300 °C; switching behavior with composite coating on current collector observed at >60 °C.





Technology challenges	Approaches to address
Safe Electrodes	•Develop materials to improve tolerance to an electrical abuse condition •Approach 1: Develop a high-voltage stable (phosphate) coating on a cobaltate cathode particle to increase the safe operating voltage of the cell and reduce the thermal dissipation by the use of a high-voltage stable coating material (cobalt phosphate). •Approach 2:Develop a composite thermal switch to shutdown cell reactions safely using coatings on the current collector substrates
Safe electrolyte	•Development of advanced high voltage, non-flammable/flame-retardant electrolytes (via electrolyte task)

PEM Fuel Cell Development

Objectives:

- Increase system lifetimes and reduce system mass, volume and parasitic power for primary and regenerative proton exchange membrane (PEM) fuel cells, and
- Enable the use of regenerative PEM fuel cells including the use of high pressure (>2000 psi) reactants to reduce tankage mass and volume.

- Focus is exclusively on Proton Exchange Membrane fuel cells and regenerative fuel cell systems

- Technical Approach is to develop:
  - "Non-flow-through" proton exchange membrane stack and customized balance-of-plant technology;
  - Advanced membrane-electrode-assemblies (MEAs) for both fuel cells and electrolyzers,
  - Balanced high-pressure electrolyzers; and
  - Thermal and reactant management technologies for electrolyzer/fuel-cell integration into regenerative fuel cell systems.

Fuel Cell Technical Approach

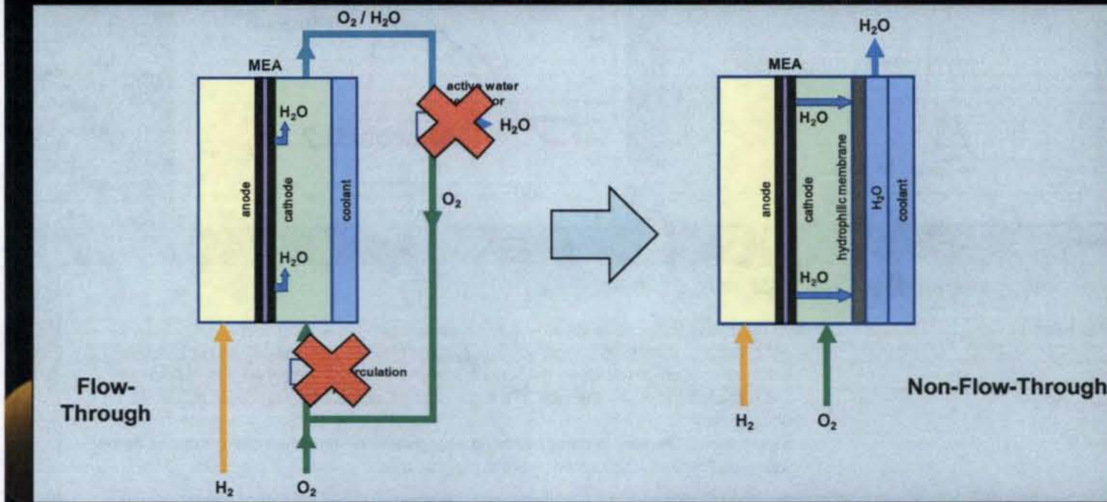
Develop "non-flow-through" proton exchange membrane fuel cell technology for a system improvement in weight, volume, reliability, and parasitic power over "flow-through" technology

Flow-Through components eliminated in Non-Flow-Through system include:

- Pumps or injectors/ejectors for recirculation
- Motorized or passive external water separators

Non-Flow-Through PEMFC technology characterized by dead-ended reactants and internal product water

- Tank pressure drives reactant feed; no recirculation
- Water separation occurs through internal cell wicking



National Aeronautics and Space Administration

Key Performance Parameters for Fuel Cell Technology Development

Customer Need	Performance Parameter	SOA (alkaline)	Current Value* (PEM)	Threshold Value** (@ 3 kW)	Goal** (@ 3 kW)
Altair: 3 kW for 220 hours continuous, 5.5 kW peak.	System power density				
	Fuel Cell	49 W/kg	n/a	88 W/kg	136 W/kg
	RFC (without tanks)	n/a	n/a	25 W/kg	36 W/kg
	Fuel Cell Stack power density	n/a	n/a	107 W/kg	231 W/kg
	Fuel Cell Balance-of-plant mass	n/a	n/a	21 kg	9 kg
Lunar Surface Systems: TBD kW for 15 days continuous operation	MEA efficiency @ 200 mA/cm²				
	For Fuel Cell	73%	72%	73%	75%
	Individual cell voltage	0.90V	0.89V	0.90V	0.92V
Rover: TBD	For Electrolysis	n/a	86%	84%	85%
	Individual cell voltage	n/a	1.48	1.46	1.44
	For RFC (Round Trip)	n/a	62%	62%	64%
	System efficiency @ 200 mA/cm²				
	Fuel Cell	71%	65%***	71%	74%
	Parasitic penalty	2%	10%	2%	1%
	Regenerative Fuel Cell****	n/a	n/a	43%	54%
	Parasitic penalty	n/a	n/a	10%	5%
	High Pressure penalty	n/a	n/a	20%	10%
Maintenance-free lifetime Altair: 220 hours (primary) Surface: 10,000 hours (RFC)	Maintenance-free operating life				
	Fuel Cell MEA	2500 hrs	13,500 hrs	5,000 hrs	10,000 hrs
	Electrolysis MEA	n/a	n/a	5,000 hrs	10,000 hrs
	Fuel Cell System (for Altair)	2500 hrs	n/a	220 hrs	220 hrs
	Regenerative Fuel Cell System	n/a	n/a	5,000 hrs	10,000 hrs

*Based on limited small-scale testing.

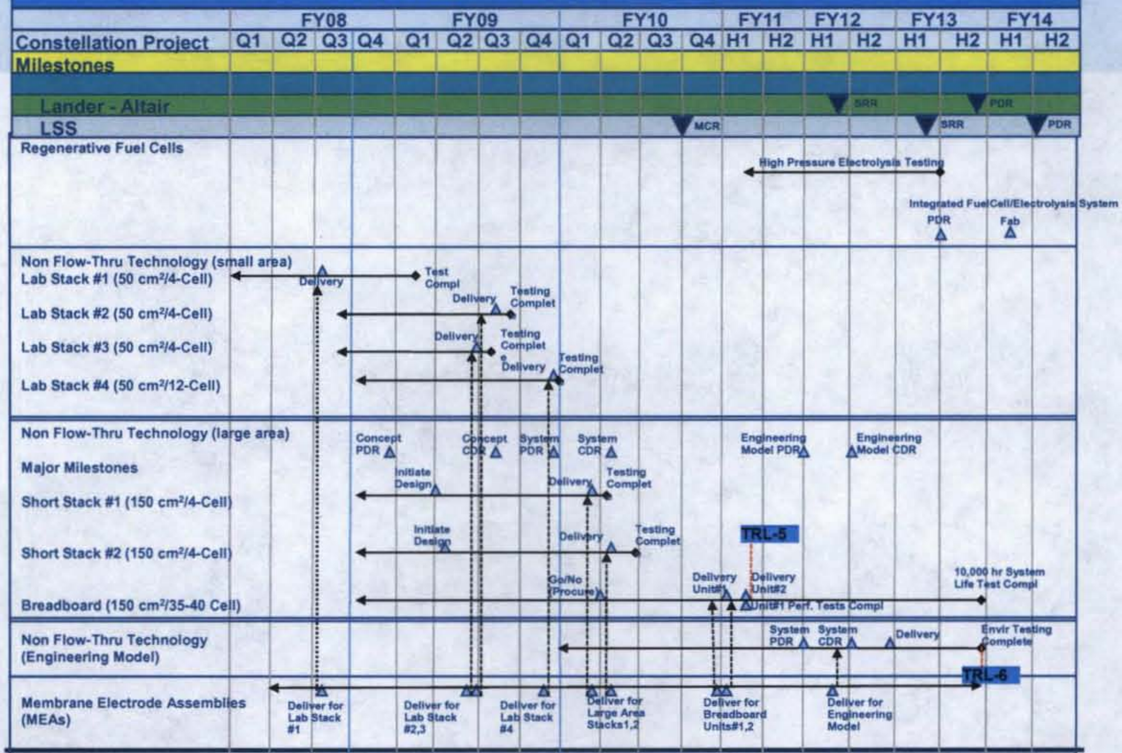
**Threshold and Goal values based on full-scale (3 kW) fuel cell and RFC technology.

***Teledyne passive flow through with latest MEA

****Includes high pressure penalty on electrolysis efficiency 2000 psi

5/22/08

Fuel Cell Master Schedule



www.nasa.gov

Progression of Primary Fuel Cell Hardware from Small-Scale to

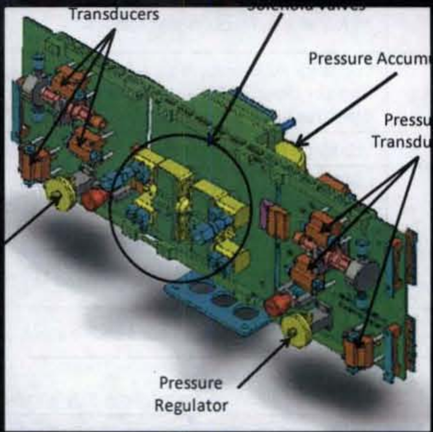
MEA infusion	Primary Fuel Cell Hardware	Hardware Description
	Laboratory Units	**Laboratory stack is 50 cm² Stainless Steel**
	Lab stack #1 is graphite. Deliverable from SBIR contract. 1st Non-Flow-Through stack at NASA.	4 cells, 40 – 80 W 1st balance-of-plant (BOP #1) developed.
X	Lab stack #2 incorporates NASA flat plate heat pipes and MEAs. Partially includes innovative assembly technology. Stainless steel plate used to accommodate heat pipe.	4 cells, 40 – 80 W
	Lab stack #3 fully integrates innovative assembly technology.	4 cells, 40 – 80 W
	Lab stack #4 fully integrates innovative assembly technology with reactant pre-humidification and product-water dissolved gas removal	12 cells, 100 – 200 W 2nd balance-of-plant (BOP #2) with autonomous operation
	Large-Area Units	**Large-area stack is 150 cm² Stainless Steel**
	Large-area cell design based on lab stack test data.	
X	Short stack has 4-cells. Two units will be delivered, both of the same design.	3rd balance-of-plant (BOP #3)
X	Breadboard system is a quarter-scale (35-40 cells) stack. This unit will be used for TRL-5 testing.	35 – 40 cells, ~1 kW 4th balance-of-plant (BOP #4), fully autonomous
	Engineering Model	**Based on Breadboard design Uses final materials (e.g. Niobium)**
X	Engineering model to be used for TRL-6 testing	150 cm², ~140 cells, 2 – 3 kW

www.nasa.gov

- Infinity Accomplishment

Integrated Balance-of-Plant

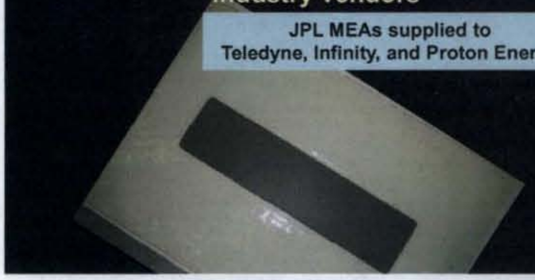
- Integrated balance-of-plant demonstrated in conjunction with the laboratory scale fuel cell stacks
- During this testing, the balance-of-plant ran on a battery source consuming only 10 watts of parasitic power to operate the fuel cell system
- A full-scale (3-kw fuel cell system) balance-of-plant will likely operate on only 50 watts or less of parasitic power (same number of components, but some components larger)
- A 2-12 kW flow-thru fuel cell system tested at GRC required over 1000 watts of parasitic power during operation
- That difference in parasitic power means that Altair would need 100-200 kg less reactants over the course of its 2-3 week mission using a non-flow-through fuel cell system vs. a flow-through system

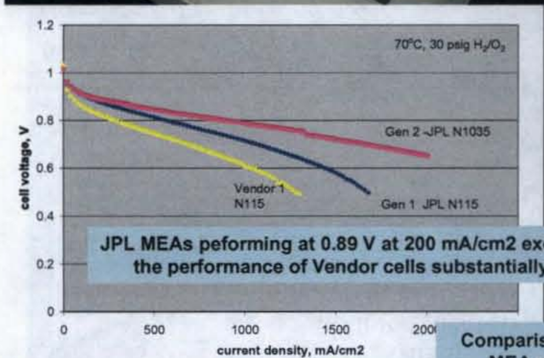


Membrane Electrode Assembly

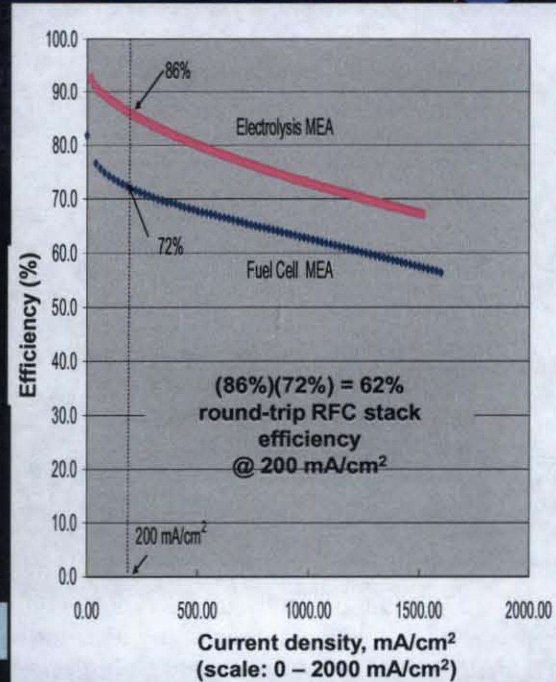
- NASA fuel cell and electrolysis MEA performance exceeds best performance of industry vendors

JPL MEAs supplied to
Teledyne, Infinity, and Proton Energy





JPL MEAs peforming at 0.89 V at 200 mA/cm2 exceed the performance of Vendor cells substantially.



Comparison of JPL's best iridium-doped ruthenium with the latest vendor MEA shows 30mV performance improvement by the NASA material.

Leveraged Activities: Fuel Cells

Fuel Cell Working Group

To facilitate knowledge transfer that will benefit the space power community by ensuring that fundamental knowledge and understanding underpins new technology development. Participants have the opportunity to receive early insights into NASA-funded technical advances, and the opportunity to provide opinions regarding the relevance of NASA-funded research.

IPP Seed Fund Program

- The Boeing Company and Teledyne Energy Systems – Human-Rated Space Power Systems Pallet Demonstrating Fuel Cells, Lithium-Ion Batteries and Advanced Thermal Management Technologies
- Hamilton Sundstrand Space Systems – Advanced High-Pressure Electrolysis System Development for NASA's Explorations Systems Program

Leveraged Activities: Fuel Cells

Phase I SBIRs

- Amsen Technologies – A Novel Heat Pipe Plate for Passive Thermal Control of Fuel Cells
- Thermacore – Titanium Heat Pipe Thermal Plane
- Infinity Fuel Cell and Hydrogen – Advanced Cathode Electrolyzer
- Giner Electrochemical Systems – Static Water Vapor Feed Electrolyzer
- Ridgetop Group – Innovative Fuel Cell Health Monitoring IC

Phase II SBIRs

- ElectroChem. – Advanced Approaches to Greatly Reduce Hydrogen Gas Crossover Losses in PEM Electrolyzers Operating at High Pressures and Low Current Densities
- Giner Electrochemical Systems – Dimensionally Stable Membrane for High Pressure Electrolyzers
- Giner Electrochemical Systems – Electrolyzer for NASA Lunar Regenerative Fuel Cells
- Distributed Energy Systems (Proton Energy) – Closed-Loop Pure Oxygen Static Feed Fuel Cell for Lunar Missions
- Giner Electrochemical Systems – Advanced Composite Bipolar Plate for Unitized Regenerative Fuel Cell/Electrolyzer Systems

•SBIRs developing alternative non-flow-through fuel cell technology, balanced high-pressure electrolysis technology, improved MEAs, and advanced balance-of-plant components for electrical and thermal management

NASA Engineering and Safety Center (NESC)
NASA Aerospace Flight Battery Systems Working Group

Addresses critical battery-related performance / manufacturing issues for NASA and the aerospace community

Objectives

- Develop/maintain/provide tools for the validation of aerospace battery technologies
- Accelerate technology readiness and provide infusion paths for emerging technologies
- Enable implementation of critical risk-mitigating test programs
- Disseminate validation/assessment tools, quality assurance and information to the NASA and aerospace battery communities
- Provide problem resolution expertise and capabilities

Working Group Makeup

- NASA Center members on core teams responsible for task implementation
- Partner agencies provide consultation and support for planning/reviewing activities

NASA Engineering and Safety Center (NESC)
NASA Aerospace Flight Battery Systems Working Group

Binding Procurements – guidelines related to requirements for the battery system that should be considered at the time of contract award

Wet Life of Ni-H_2 Batteries – issues/strategies for effective storage and impact of long-term storage on performance and life

Generic Guidelines for Lithium-ion Safety, Handling and Qualification – Standardized approaches developed and risk assessments

- Lithium-ion Performance Assessment – survey of manufacturers and capabilities to meet mission needs. Guidelines document generated
- Conditions Required for using Pouch Cells in Aerospace Missions – focus on corrosion, thermal excursions and long-term performance issues. Document defining requirements to maintain performance and life
- High Voltage Risk Assessment – focus on safety and abuse tolerance of battery module assemblies. Recommendations of features required for safe implementation
- Procedure for Determination of Safe Charge Rates – evaluation of various cell chemistries and recommendation of safe operating regimes for specific cell designs

Lithium-ion Battery Source Material Availability – provide additional support for the governmental Title 3 effort aimed at ensuring a constant supply of source material

NASA Aerospace Battery Workshop – government-industry forum focused on battery industry developments and issues (held annually in the Fall)

- ISS Update – Penni Dalton